

NEUTRINO PHYSICS: AN EXPERIMENTAL OVERVIEW

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The field of neutrino physics is currently very exciting, with several recent results pointing to new physics. I will give an overview of the current experimental situation, focusing primarily on neutrino oscillation results. The data are not entirely consistent however, and puzzles remain. I will then review the new experiments which are poised to solve the outstanding puzzles.

1. Introduction

Neutrinos are now known to have mass and to mix. It is still not known exactly how they fit into the theoretical picture, however. In the baseline Standard Model, neutrinos are massless, and extensions to the Standard Model are required to explain their small masses and the observed oscillation phenomena. These observations can be accommodated in GUTs, and perhaps more exotic scenarios such as extra dimensions¹). Neutrinos are also important for cosmology, and play a role in the early universe. Even a tiny ν mass is sufficient for neutrinos to make up a significant portion of the total mass of the Universe. To further understanding, we must turn to experiment: we must quantify knowledge of masses, map the mixing matrix, and determine whether CP violating phases are present for neutrino as well as quark mixing. We must determine whether sterile neutrinos exist. Another important question is whether neutrinos are Majorana or Dirac (i.e. whether or not they are equivalent to their antiparticles), which can be probed experimentally by searching for double beta decay, or dipole moments of neutrinos.

Here I will focus on one significant aspect of experimental neutrino physics: the search for neutrino oscillations. But before proceeding, I will pause to welcome the last neutrino to the family: τ leptons from the interactions of ν_τ 's have finally been observed by the DONUT (Direct Observation of the Nu Tau) experiment at Fermilab². This experiment used a prompt ν_τ beam and an active emulsion detector to look for the “kink” indicating a ν_τ -induced τ lepton decaying \sim millimeters from the interaction vertex. DONUT collaborators find four “long decay” events (which have a measured τ parent to the decay), where they expect 4.1 ± 1.4 signal events, and 0.41 ± 0.15 background events. More analyses are in progress.

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2. Neutrino Mass and Oscillations

2.1. Neutrino Oscillations

Neutrino oscillations arise from straightforward quantum mechanics. We assume that the N neutrino flavor states $|\nu_f\rangle$, which participate in the weak interactions, are superpositions of the mass states $|\nu_i\rangle$, and are related by a unitary mixing matrix:

$$|\nu_f\rangle = \sum_{i=1}^N U_{fi} |\nu_i\rangle. \quad (1)$$

For the two-flavor case, assuming relativistic neutrinos, it can easily be shown that the probability for flavor transition is given by

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E), \quad (2)$$

for $\Delta m^2 \equiv m_2^2 - m_1^2$ in eV^2 . L (in km) is the distance traveled by the neutrino and E in GeV is its energy. Several comments are in order:

- Note that in this equation the parameters that experimenters try to measure (and theorists try to derive) are $\sin^2 2\theta$ and Δm^2 . L and E depend on the experimental situation.
- The neutrino oscillation probability depends on mass squared differences, not absolute masses.
- The neutrino mixing matrix can be easily generalized to three flavors, and the transition probabilities computed in a straightforward way.
- For three flavors, there are only two **independent** Δm^2 values.
- If the mass states are not nearly degenerate, one is often in a “decoupled” regime where it is possible to describe the oscillation as effectively two-flavor, i.e. following an equation similar to 2, with effective mixing angles and mass squared differences. I will assume a two-flavor description of the mixing in most cases here.
- “Sterile” neutrinos, ν_s , with no normal weak interactions, are possible in many theoretical scenarios (for instance, as an isosinglet state in a GUT¹).

3. The Three Experimental “Hints”

There are currently three experimental “hints” of neutrino oscillations. These indications are summarized in Table 1. I will now examine the current status of each of these observations.

3.1. Solar Neutrinos

Table 1. Experimental evidence for neutrino oscillations.

ν source	Experiments	Flavors	E	L	Δm^2 sensitivity (eV^2)
Sun	Chlorine	$\nu_e \rightarrow \nu_x$	5-15 MeV	10^8 km	$10^{-12} - 10^{-10}$ or $10^{-6} - 10^{-4}$
	Gallium				
Cosmic ray showers	Water Cherenkov	$\nu_\mu \rightarrow \nu_x$	0.1-100 GeV	$10 - 10^5$ km	$10^{-2} - 10^{-3}$
	Iron calorimeter				
	Upward muons				
Accelerator	LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	15-50 MeV	30 m	0.1-1
		$\nu_\mu \rightarrow \nu_e$	20-200 MeV		

The deficit of solar neutrinos was the first of these “hints” to be observed. The solar neutrino energy spectrum is well predicted, and depends primarily on weak physics, being rather insensitive to any solar physics. Three types of solar neutrino detectors (chlorine, gallium and water Cherenkov), with sensitivity at three different energy thresholds, together observe an energy-dependent suppression which cannot be explained by any solar model (standard or non-standard)³.

The observed suppression in all three experiments can be explained by neutrino oscillation at certain values of Δm^2 and mixing angle: see Figure 1. The allowed regions at higher values of Δm^2 (“small mixing angle”, “large mixing angle” and “low”) are those for which matter effects in the Sun come into play. The solutions at very small Δm^2 values are the vacuum oscillation solutions. Figure 1 shows the mixing angle axis plotted as $\tan^2 \theta$, rather than as the more conventional $\sin^2 2\theta$, to make evident the difference between $0 < \theta < \pi/4$ and $\pi/4 < \theta < \pi/2$: these regions are not equivalent when one considers matter effects⁴.

The measured energy spectrum of solar neutrinos is a potential “smoking gun” for neutrino oscillations: a distortion from the expected shape would be hard to explain by other than non-standard weak physics. The latest Super-K solar neutrino spectrum shows no evidence for distortion⁵. Another “smoking gun” solar neutrino measurement is the day/night asymmetry: electron neutrinos may be regenerated in the Earth from their oscillated state for certain oscillation parameters. The latest measured Super-K day/night asymmetry is $\frac{D-N}{(D+N)/2} = -0.034 \pm 0.022^{+0.013}_{-0.012}$: regeneration is therefore a relatively small effect, if it is present at all. Together, the energy spectrum and day/night observations place strong constraints on solar neutrino parameters. In particular, Figure 1 shows the Super-K results overlaid on the global flux fit parameters: large mixing angles are favored, and the small mixing angle and vacuum solutions from the global flux fit are disfavored at 95% C.L.. In addition, all global flux fit $\nu_e \rightarrow \nu_s$ solutions are disfavored at 95% C.L.. See also reference 6 from these proceedings.

3.2. Atmospheric Neutrinos

Atmospheric neutrinos are produced by collisions of cosmic rays with the upper atmosphere. Energies are in the range from 0.1 GeV to 100 GeV. Atmospheric neu-

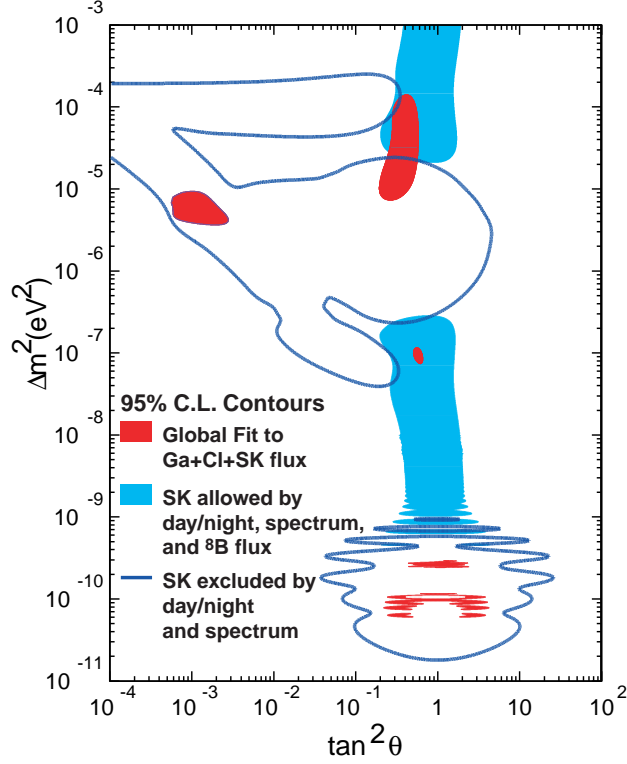


Fig. 1. Solar neutrino parameter space: the dark areas show the global flux fit solutions. The interiors of the dark lines indicate Super-K's excluded regions; the light shaded areas indicate Super-K's allowed regions.

trinos can be observed coming from all directions. At neutrino energies $\gtrsim 1$ GeV, for which the geomagnetic field has very little effect on the primaries, by geometry the neutrino flux should be up-down symmetric. Although the absolute flux prediction has $\sim 15\%$ uncertainty, the flavor ratio (about two muon neutrinos for every electron neutrino) is known quite robustly, since it depends on the well-understood decay chain $\pi \rightarrow \mu \nu_\mu \rightarrow e \nu_e \bar{\nu}_\mu$. The Super-K result of 1998⁷ showed a highly significant deficit of ν_μ events from below, with an energy and pathlength dependence as expected from equation 2. The most recent data constrain the two-flavor $\nu_\mu \rightarrow \nu_\tau$ oscillation parameters to a region as shown in Figure 2. The latest results from Soudan 2⁸ (an iron tracker) and from MACRO's⁹ upward-going muon sample are consistent with the Super-K data.

Recently, Super-K has also been able to shed some light on which flavors are involved in the muon neutrino disappearance. Assuming a two-flavor oscillation, the missing ν_μ 's could have oscillated into either ν_e , ν_τ or ν_s . The oscillation cannot be pure $\nu_\mu \rightarrow \nu_e$, because there is no significant excess of ν_e from below. In addition, the CHOOZ¹² and Palo Verde¹³ experiments have ruled out disappearance of reactor $\bar{\nu}_e$, for similar parameters. Three-flavor fits of the Super-K data have also

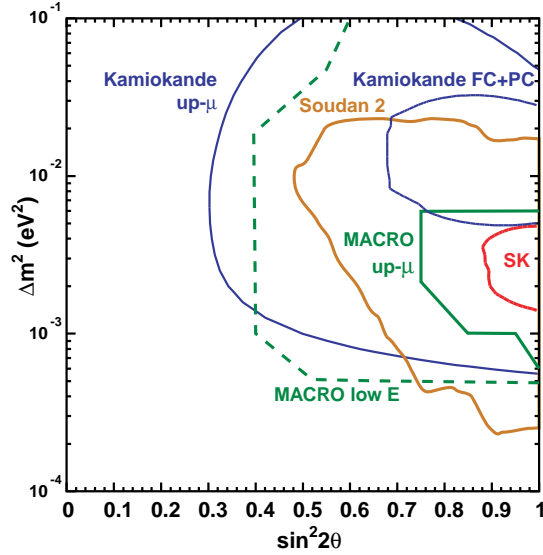


Fig. 2. Atmospheric neutrino oscillation parameter space. Parameters to the right of the contours shown are allowed by the experiments.

been done; small mixing to ν_e is allowed¹¹.

It is difficult to test the $\nu_\mu \rightarrow \nu_\tau$ hypothesis directly. Super-K expects only tens of charged current (CC) ν_τ interactions in the current sample, and the products of such interactions in the detector are nearly indistinguishable from other atmospheric neutrino events. However, recently Super-K has employed two strategies to distinguish $\nu_\mu \rightarrow \nu_\tau$ from $\nu_\mu \rightarrow \nu_s$ ¹⁰. First, one can look for an angular distortion of high-energy neutrinos due to matter effects of sterile neutrinos propagating in the Earth: unlike ν_τ 's, sterile neutrinos do not exchange Z^0 's with matter in the Earth, resulting in an MSW-like effect that effectively suppresses oscillation. The effect is more pronounced at higher energies. Such distortion of the high-energy event angular distribution is not observed. Second, one can look at neutral current (NC) events in the detector: if oscillation is to a sterile neutrino, the neutrinos “really disappear” and do not interact via NC. A NC-enriched sample of multiple-ring Super-K events shows no deficit of up-going NC events. Together, these measurements exclude two-flavor $\nu_\mu \rightarrow \nu_s$ at 99% C. L., for all parameters allowed by the Super-K fully-contained events.

3.3. LSND

The third oscillation hint is the only “appearance” observation: the Liquid Scintillator Neutrino Detector (LSND) experiment at Los Alamos has observed an excess of $\bar{\nu}_e$ events¹⁴ from a beam which should contain only $\bar{\nu}_\mu$, ν_e and ν_μ from positive pion and muon decay at rest. The result is interpreted as ~ 20 -50 MeV $\bar{\nu}_\mu$'s oscillating over a 30 m baseline. The LSND collaboration also observes an excess of higher

energy (60-200 MeV) electrons¹⁵, presumably due to ν_e 's oscillated from ν_μ 's from pion decay in flight. This observation is consistent with the oscillation hypothesis. See Figure 3 for the corresponding allowed region in parameter space. The large mixing angle part of this range is ruled out by reactor experiments.

An experiment at Rutherford-Appleton Laboratories called KARMEN, which has roughly similar neutrino oscillation sensitivity (17.5 m baseline) as does LSND, does not however confirm the LSND result¹⁶. This detector expects fewer signal events than does LSND, but has a stronger background rejection due to the pulsed nature of their neutrino beam. However, due to somewhat different sensitivity, KARMEN's lack of observation of $\bar{\nu}_e$ appearance cannot rule out all of the parameter space indicated by LSND: see Figure 3.

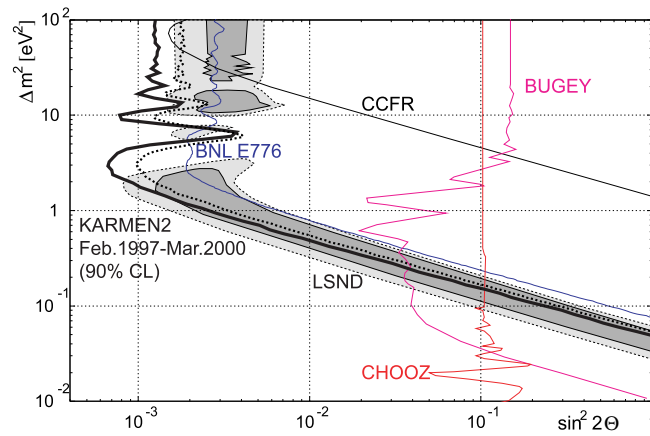


Fig. 3. LSND parameter space. The shaded region indicates the parameters allowed by LSND. The region to the right of the dark line is excluded by KARMEN. The Bugey reactor experiment excludes the large mixing angle parameters. Plot from K. Eitel¹⁶.

3.4. Accelerator Searches at High Δm^2

Another region of parameter space which has been recently been explored is in the regime where $\Delta m^2 > 1 \text{ eV}^2$. This is an interesting region for cosmological reasons: neutrino masses in this range could have a significant effect on cosmological models. However, no signal has been found in this region. In particular, the CHORUS and NOMAD experiments at CERN, which observed the same ν_μ beam ($\langle E_\nu \rangle \sim 25 \text{ GeV}$, baseline $\sim 600 \text{ m}$) with quite different detector technologies (emulsion and electronic tracking, respectively), have both excluded $\nu_\mu \rightarrow \nu_\tau$ at 90% C.L. for $\Delta m^2 \gtrsim 0.7 \text{ eV}^2$ at maximal mixing, down to $\sin^2 2\theta \gtrsim 5 - 8 \times 10^{-4}$ for $\Delta m^2 \gtrsim 100 \text{ eV}^2$ ^{17,18}.

4. Where Do We Stand?

Now we can step back and view the big picture. Where do we stand? The current

experimental picture for the three oscillation signal indications can be summarized:

- For solar neutrino parameter space ($\nu_e \rightarrow \nu_x$): Super-K's day/night and energy spectrum data disfavor small mixing angle and vacuum solutions; large mixing is favored. Pure $\nu_\mu \rightarrow \nu_s$ is disfavored.
- For atmospheric neutrino parameter space, evidence from Super-K, Soudan 2 and MACRO is very strong for $\nu_\mu \rightarrow \nu_x$. Furthermore, Super-K's data favor the $\nu_\mu \rightarrow \nu_\tau$ hypothesis over the $\nu_\mu \rightarrow \nu_s$ one.
- The LSND indication of $\nu_\mu \rightarrow \nu_x$ still stands; KARMEN does not rule out all of LSND's allowed parameters.

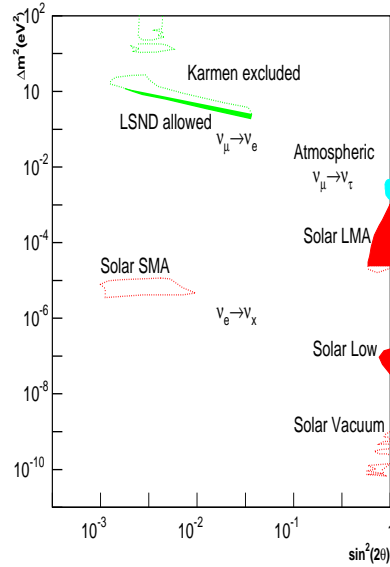


Fig. 4. Overall parameter space: the current picture. Solid regions are allowed by the latest data; dotted regions encompass regions allowed until recently.

What do these data mean? There is an obvious problem. Under the assumption of three generations of massive neutrinos, there are only two independent values of Δm^2 : we must have $\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$. However, we have three measurements which give Δm^2 values of three different orders of magnitude. So, if each hint represents two-flavor mixing, then something must be wrong. Three-flavor fits are unsatisfactory¹⁹. One way to wriggle out of this difficulty is to introduce another degree of freedom in the form of a sterile neutrino (or neutrinos). (We cannot introduce another light active neutrino, due to the Z^0 width measurements from LEP, which constrain the number of active neutrinos to be three²⁰: any new light neutrino must be sterile). Although pure mixing into ν_s is now disfavored by Super-K solar and atmospheric neutrino results, a sterile neutrino is still viable as part of

some four-flavor mixing¹⁹. Of course, it is also possible that some of the data are wrong or misinterpreted. Clearly, we need more experiments to clarify the situation.

5. What's Next?

So what's next? I will cover the next experiments for each of the interesting regions of parameter space.

5.1. LSND Neutrino Parameter Space

The next experiment to investigate the LSND parameter space will be BooNE (Booster Neutrino Experiment). This will look at ~ 1 GeV neutrinos from the 8 GeV booster at Fermilab, at a baseline of about 500 m (with a second experiment planned at longer baseline if an oscillation signal is seen). This experiment can test ν_μ disappearance, but is primarily designed to test $\nu_\mu \rightarrow \nu_e$ at about the same L/E as LSND. Since the energy is higher, and the backgrounds are different, systematics will presumably be different from those at LSND. BooNE, which will start in December 2001, expects about 500 oscillation signal events per year at LSND parameters, and expects to cover all of LSND space in one year of running²¹.

5.2. Solar Neutrino Parameter Space

A great variety of experiments are working towards an understanding of solar neutrinos. The first new experiment among these is the SNO (Sudbury Neutrino Observatory) experiment²². This experiment contains 1 kton of D₂O, aiming to measure CC and NC breakup reactions, as well as elastic scattering (ES). Information about solar neutrino oscillations will be obtained by observing the distortion of the CC energy spectrum, as well as CC/NC and CC/ES ratios. SNO has been taking data for about one year, and this summer SNO reported its first CC data²³. The first NC data and oscillation analyses are expected soon.

Two new low energy threshold scintillator detectors are on the very near horizon. Borexino at the Gran Sasso Laboratory in Italy²⁴ is a 300 ton scintillator experiment, with very low radioactive background. It will start in 2002. Borexino's aim is to see the solar 0.86 MeV ^7Be line. Measurement of day/night and seasonal variations of this line should give very good sensitivity to vacuum and "low" solar neutrino oscillation solutions. KamLAND is a 1 kton scintillator detector at the Kamioka mine in Japan²⁵. This detector, which should start operation in 2001, intends to study the large mixing angle part of solar parameter space with *reactor* neutrinos: it will measure the sum of the fluxes of $\bar{\nu}_e$ from reactors within about 500 km in Japan and Korea. KamLAND also hopes to study solar neutrinos directly. There are also a number of innovative new solar neutrino experiments aiming to look at the very low energy pp solar flux²⁶.

5.3. Atmospheric Neutrino Parameter Space

For atmospheric neutrino parameter space, the next steps are the "long-baseline"

experiments, which aim to test the atmospheric neutrino oscillation hypothesis directly with an artificial beam of neutrinos.

The first of these is the K2K (KEK to Kamioka) experiment²⁷, which started in March 1999, and which saw the first artificial long-distance neutrinos in June 1999. K2K sends a beam of $\langle E_\nu \rangle \sim 1$ GeV ν_μ 250 km across Japan to the Super-K experiment. K2K can look for ν_μ disappearance (the beam energy is not high enough to make significant τ 's). Preliminary results do show a deficit of observed neutrinos: $40.3^{+4.7}_{-4.6}$ beam events in the fiducial volume are expected, but only 27 are seen, which disfavors no oscillations at the 2σ level. About 25% of K2K data has been taken.

The MINOS experiment²⁸, to start in 2003, will send a beam from Fermilab to Soudan, with a beam energy of 3 – 20 GeV, and a baseline of 730 km. The far detector is a magnetic iron tracker. CNGS (Cern Neutrinos to Gran Sasso)²⁹, a ~ 20 GeV ν_μ beam from CERN to the Gran Sasso 730 km away, will start in 2005. These long baseline experiments, thanks to high beam energies and high statistics, can expand the search beyond ν_μ disappearance: they can also look for ν_e appearance at small mixing, and possibly also for τ appearance.

A possibility on the farther horizon for atmospheric neutrino parameter space is a neutrino factory: a muon storage ring would produce copious, and well-understood, 20-50 GeV neutrinos from muon decay³⁰. Detectors at 3000-7000 km baselines could study atmospheric neutrino oscillation parameters with unprecedented precision, could possibly measure $\nu_e - \nu_\tau$ mixing, and could even perhaps find CP violation (although this would have to be disentangled from matter effects in the Earth). Other possibilities being explored are more conventional ν beams of high intensity³¹.

Figure 5 summarizes the reach of the next generation of neutrino experiments.

6. Other Neutrino Experiments

This review has focused on neutrino oscillation studies. However, I do not wish to leave the impression that oscillations are all of neutrino physics. There are many other ways of clarifying the neutrino picture, and I will mention some of them briefly here.

- *Kinematic Absolute Mass Limits:* As noted above, neutrino oscillation measurements say nothing about absolute masses of the mass states. Although the kinematic mass searches are difficult, the concept is simple: look for missing energy. The traditional tritium beta decay spectrum endpoint experiments now have limits for absolute ν_e mass of $\lesssim 2.5$ eV/ c^2 , and prospects are good for improvement down to $\lesssim 0.5$ eV/ c^2 ^{32,33}. The ν_μ and ν_τ mass limits are currently 190 keV/ c^2 ³⁴ and 15.5 MeV/ c^2 ³⁵ respectively.
- *Double Beta Decay:* Another way of getting at absolute neutrino mass is to look for neutrinoless double beta decay, $(N, Z) \rightarrow (N - 2, Z + 2) + e^- + e^-$. Such a decay is only possible if the neutrino has mass, and is Majorana. The current lowest mass limits from non-observation of double beta decay are

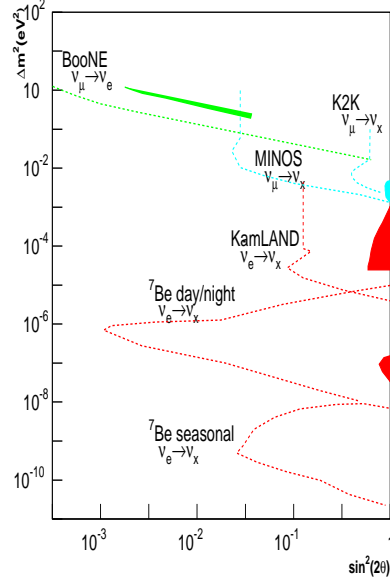


Fig. 5. Sensitivities of the next neutrino oscillation experiments.

about $\langle m_\nu \rangle_e < 0.2 \text{ eV}/c^2$ ^{36,37}. Many new experiments are being built, and prospects are good for improving the limits down to $0.01 \text{ eV}/c^2$ ³⁸.

- *Neutrino Magnetic Moment:* A non-zero non-transition magnetic moment implies that neutrinos are Dirac and not Majorana. The best limits on neutrino magnetic moment³⁹ are astrophysical. The current best laboratory limits are $\mu_\nu \lesssim 10^{-10} \mu_B$. The MUNU experiment, which measures elastic scattering of reactor $\bar{\nu}_e$, will improve this limit by an order of magnitude⁴⁰.
- *Supernova Neutrinos:* A supernova is a “source of opportunity” for neutrino physics: we can expect a giant burst of neutrinos of all flavors from a core collapse in our Galaxy about once every 30 years. Many of the large neutrino experiments – Super-K, SNO, Borexino, KamLAND, LVD and AMANDA – are sensitive⁴¹. We may be able to extract absolute mass information from time of flight measurements, as well as some oscillation information by looking for spectral distortion.
- *High Energy Neutrino Astronomy:* Long string water Cherenkov detectors (AMANDA, Baikal, Antares, Nestor) in ice and water, are embarking on a new era of high energy neutrino astronomy⁴². From the $\gtrsim 10 \text{ GeV}$ neutrino signals in these detectors, we can learn about astrophysical sources of neutrinos, as well as about oscillation at high energy.

- *Cosmology:* Finally, neutrinos play a significant role in cosmology⁴³. They may make up some non-negligible component of the dark matter (although this is now thought to be small, in order to be consistent with galactic structure formation). Cosmological considerations constrain the sum of absolute masses of the states to ~ 10 eV or less. The ultra low energy (1.95 K) big-bang relic neutrinos⁴⁴, which are expected to permeate the universe with a number density of 113 cm^{-3} , remain an experimental challenge.

7. Summary

In summary, I will list recent highlights of experimental neutrino physics:

- The DONUT experiment has directly detected ν_τ -induced τ 's for the first time.
- Super-K's solar neutrino results favor large mixing and disfavor the small mixing and vacuum oscillation solutions of the global flux fit. Pure $\nu_e \rightarrow \nu_s$ mixing is also disfavored for all parameters.
- The SNO experiment has presented its first CC data.
- Super-K atmospheric neutrinos favor $\nu_\mu \rightarrow \nu_\tau$ over $\nu_\mu \rightarrow \nu_s$ based on angular distributions of high energy events, and of a NC-enriched sample.
- With 25% of data taken, K2K's deficit of beam ν_μ 's disfavors the no-oscillation hypothesis.
- The LSND $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) signal is not ruled out by the latest KARMEN data, and will be tested by BooNE.

It is now quite certain that neutrinos have mass and mix. The details of the picture are getting more clear, but many puzzles remain. The data taken together are inconsistent with the mixing of three families of active neutrinos, and we still do not know whether all results are correct, or whether wider assumptions are needed. We do not have enough information to know how to fit the observations into extensions of the Standard Model. However, many new experiments are poised to answer these questions, and clearly, the next ten years will be extremely interesting.

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